# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*

**2. REPORT TYPE**
Technical Papers

**3. DATES COVERED** *(From - To)*

**4. TITLE AND SUBTITLE**

**5a. CONTRACT NUMBER** N/A

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**

**5d. PROJECT NUMBER**
2308

**5e. TASK NUMBER**
M19B

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

**8. PERFORMING ORGANIZATION REPORT**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

**15. SUBJECT TERMS**

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| | | | | | Leilani Richardson |
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | **19b. TELEPHONE NUMBER** *(include area code)* |
| Unclassified | Unclassified | Unclassified | A | | (661) 275-5015 |

21 separate items enclosed



103 049

TP-FY99-0140

✓ Spreadsheet
✓ DTS

2308M9B

MEMORANDUM FOR PRS (Contractor/In-House Publication)

FROM: PROI (TI) (STINFO)

14 June 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0140
Lufty, Muntz and Ketsdever, "Investigation of the Operational Envelope of the CHAFF-4 Plume and Contamination Facility"

**AIAA**

**(Public Release)**

# Investigation of the Operational Envelope of the CHAFF-4 Plume and Contamination Facility

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## ABSTRACT

Interest in realistic simulation of the space environment as applied to the study of spacecraft contamination and thruster plumes has led to the development of the CHAFF-4 facility. CHAFF-4 uses a multi-fin cryogenically cooled array (~20K) that completely envelops the interior of the chamber providing an available condensing surface area of 590 $m^2$. The geometry of the array capitalizes on the fact that both neutral and ion species from spacecraft propulsion systems predominantly undergo diffuse reflections when impacting at angles normal to the surfaces they encounter. Preliminary figures of merit for the equivalent altitude possible for various propulsion systems vary between 150-350 km (depending on thruster type). The effective pumping speed is predicted to be between $3 \times 10^7$ and $1 \times 10^8$ liters/sec. The facility is expected to accommodate thruster power levels up to 3500 W without the use of supplementary liquid helium, although infrastructure permitting its use is available. Developmental considerations and design issues are discussed in view of basic principles of plume testing and contamination, in order to ensure the integrity of phenomena that are observed in the facility. Provisions for the simulation of high-speed LEO flow environments have been incorporated in the design, and the corresponding pumping requirements are well within the capabilities of CHAFF-4.

## INTRODUCTION

The interaction of spacecraft thruster plumes with a spacecraft and the ambient low-Earth orbit (LEO) environment is of interest to spacecraft mission planners for a wide variety of reasons. Although spacecraft propulsion systems are mission enabling, they can also be sources for particulate, molecular and radiation contamination on and near spacecraft surfaces [1,2]. In early 1995, the need for a national facility capable of performing meaningful LEO plume and contamination studies was identified by researchers at the University of Southern California and the Air Force Research Laboratory. One motivation was the present lack of a facility that could be used for ground-based studies of the many thruster interaction phenomena associated with the LEO high speed, rarefied flow environment. A second objective was to provide a facility that would be able to faithfully simulate the low pressures experienced by thrusters in space during operation. A matter of significance, particularly for electric thrusters such as the Hall effect devices that operate based on a discharge directly exposed to the space environment. The same objectives are also of vital importance for meaningful contamination studies.

The complex interactions that propulsion systems encounter in space as well as the thruster's impact on satellite systems have brought about the need to test these devices in specially designed vacuum facilities. It is important to note that there are few, if any, present-day vacuum facilities that were built with an infrastructure specifically tailored to address the concerns of contamination and plume diagnostic science. A notable historical exception was the JPL Molsink facility [3]. However, none of the current or past facilities provide a simulated LEO high-speed flow environment. More typical are vacuum vessels that

Support for this work was received from the Air Force Office of Scientific Research, the Army Research Office, and the University of Southern California. The authors would like to thank Robert Smith, Herb Llyod, Marc Young, Arthur Alves, Amanda Green and Matt Franklin for their efforts in constructing this facility.

maintain reasonable background pressures in order to allow the operation of various propulsion systems [4,5]. Such facilities are designed to determine operational constraints and parameters; however, they are not necessarily appropriate for detailed plume and contamination studies due to the relatively high background concentrations of propellant molecules.

Taking advantage of the relatively low operating costs of a university based facility, the David P. Weaver Collaborative High Altitude Flow Facility (CHAFF) was conceived as a place where synergistic government, university and industry research and preliminary development activities could be nurtured. The CHAFF is actually a complex of four high-altitude flow facilities as shown in Fig. 1. CHAFF-1 is a cryogenically pumped small plume and molecular beam facility. CHAFF-2 is for the study of high-altitude liquid vaporization phenomena. CHAFF-3 is a micropropulsion test chamber. CHAFF-4 is the new contamination and plume diagnostics LEO flow simulator. The realization of the CHAFF concept and the operation of CHAFF-4 are imminent. This paper documents the design considerations and the unique capabilities of the new CHAFF-4 facility.

Unlike thruster lifetime test chambers, CHAFF-4 was designed from its inception as a state-of-the-art contamination and plume diagnostics facility, including the presence of a high-speed external LEO flow environment. CHAFF-4 will enable researchers to measure intrinsic contamination footprints for a wide variety of electric as well as modest chemical thrusters (up to 5 g/sec flow rate). In addition, detailed and accurate near plume characterizations will be possible for the same variety of propulsion systems. Achieving the design conditions for CHAFF-4 is possible since the flux of reflected and sputtered material infiltrating the volume(s) of interest is drastically reduced. This was accomplished by developing a cryogenic array pumping system, which condenses thruster efflux by enhancing the probability of multiple interactions with cold surfaces (77 and 20 K) before most species can scatter back into the chamber interior.

The low background concentration of propellant fragments and the external high-speed flow capability make CHAFF-4 a unique facility. It is clear that one such facility is worth constructing. It will not be clear until spacecraft propulsion research results from CHAFF-4 are available whether or not there is a need for more than one such facility. It is for this reason that the original CHAFF concept was to make CHAFF-4 available to the community of government, university and industry investigators.

## EXHAUST PLUME AND CONTAMINATION STUDIES

The design of CHAFF-4 is derived from a few basic criteria that are outlined in this section. A convenient framework for the discussion are the principles of the rarefaction of exhaust plume interaction with background gases which were formulated by Muntz et al [6]. The thruster exhaust has two characteristic lengths, the mean free path $\lambda_j$ of the exhaust gases in the background gas and the distance from the thruster, $r_p$, that is essentially free from the penetration of background gas into the exhaust gas plume. These characteristic lengths are most conveniently defined along the centerline of the exhaust plume. Exhaust plumes universally appear to be radial expansions from a source near the thruster exit (providing the observation is made at greater than say 10 diameters from the exit).

The characteristic plume dimensions $\lambda_j$ and $r_p$ are measured from the source and have the form

(1)

(2)

where for SI units $K_1$ is a constant of order $10^7$, $n_a$ is the atmospheric or background number density, $\Omega_{jB}$ is the momentum transfer collision cross-section between the exhaust gas species and the atmosphere or background species, $T_h$ is the propulsion system's thrust level in Newtons, and $V_{EX}$ is the propellant's exhaust speed. Generally $\lambda_j > \lambda_A$ primarily because $\Omega_{jB} < \Omega_A$ where $\lambda_A$ and $\Omega_A$ refer to the atmosphere's mean free path and its average collision cross-section.

A plume Knudsen number can characterize the rarefied interaction between exhaust gases and the atmosphere which takes the form $Kn_p = \lambda_j / r_p$. If $Kn_p >> 1$, the interactions can be considered as two separable molecular scattering events [6]. One

is the effective stopping of the exhaust gases relative to the atmosphere in a distance $\lambda_j$ and the other is the diffusive penetration of the atmospheric gases into the plume to a distance $r_p$.

It is instructive to cast the description of exhaust plume interactions outlined above into the framework of ground based thruster and plume investigations. Consider the atmospheric mean free path $\lambda_A$; by 150 km, it is equivalent to the dimensions of any reasonable ground based facility. Since $\lambda_j \geq \lambda_A$ for practically all circumstances of any significance, it is clear that full scale thruster investigations relating to complete plume-background interactions are not possible. However, providing $r_p << \lambda_j$ as is the case for small nozzle thrusters or for electric thrusters, significant studies can be made of the near plume region (close to the thruster in analogy to the near wake region of re-entry vehicles). This is of course assuming that the thruster is not creating its own background gas in the facility. Thus, an initial requirement is that the facility provides an inner envelope that efficiently suppresses the reflection of thruster exhaust gases so that the large majority of background gas in the facility can be injected separately and be characteristic of the upper atmosphere, not products of the thruster exhaust gases. To accomplish this, the entire inner surface of the facility is designed as a pumping surface.

It is perhaps worthwhile to point out that for studying the basic operation of nozzle thrusters the penetration of background gas into the plume is in all cases far downstream of the thruster in terms of exit diameter ($D_O$). That is $r_p >> D_O$ because of the necessity for maintaining continuum flow conditions in the nozzle expansion. As a consequence the background pressure and composition for studying nozzle thruster operating characteristics is not particularly critical.

For ion electric thrusters there is an entirely different situation. Note from Eq (1) that for a fixed thrust it is not surprising that the background gases are basically free to penetrate to the thruster exit in these devices. Thus, investigation of ion electric thruster operations in a facility is potentially more sensitive to facility induced background conditions. In fact such effects may be very subtle since the species (for example Xe) generated by the thruster in the facility is the same as the propellant. Consequently the effects of the background may be hard to discern.

For contamination studies, there are two important effects which must be minimized. First, it is important to minimize the effects of propellant gas reflections with chamber surfaces particularly in the backflow regions. Experimental results in this region can be dominated by propellant molecules which enter this region due to collisions with the chamber walls. Second, the effects of propellant molecules scattering from background gases must be negligible. This can only be accomplished by maintaining very low background pressures in the facility. Again to minimize these effects, the entire inner surface of the facility is designed as a pumping surface not only for increased pumping area but also to minimize surface scattering.

## HIGH ALTITUDE BACKGROUND DENSITY CONSIDERATIONS

For the study of spacecraft propulsion systems in a ground-based facility there are three basic propellant populations that need to be addressed;

- energetic ions (100 to 3000 eV) from Hall effect and conventional ion thrusters along with a smaller number of very fast neutrals resulting from charge exchange,
- cold neutrals from the unionized component of ion thrusters (up to 50% of mass flow) as well as from cold or resistojet thrusters,
- fast neutrals (~1 eV) from chemical or arc discharge thrusters.

One objective of the CHAFF-4 design effort was to achieve an extremely small background concentration of propellant gas. Consider the characteristics of a typical thruster test facility with an internal surface area that has some relatively modest fraction ($f_p$) occupied by pump inlets or pumping surface. The exhaust mass flow of a thruster system is generally stopped and randomized by the facility's surfaces. The random motion of the scattered propellant molecules drives them into the pump inlets. The background number density of propellant $n_{B,pr}$ can be calculated by the following expression

where $m_{pr}$ and $T_p$ are the mass of the propellant molecule and the temperature of the propellant gas as it is driven to the pumping surface, respectively (for cryosorption pumps this is about 80 K). $T_B$ is the background gas temperature and $A_S$ is the chamber's surface area.

As one example, Randolph et al [7] suggest that for studies of stationary plasma thrusters reliable results can be obtained for $n_B \leq 1.6 \times 10^{18}\ m^{-3}$. For near plume investigations they suggest $n_B \leq 4 \times 10^{17}\ m^{-3}$. For other types of thrusters different criteria will apply. Clearly a critical point, at least for plume studies, is reached when the background mean free path $\lambda_B \leq l_f$, where $l_f$ is the largest internal dimension of the facility.

For reasons such as investigations of back flow contamination, the effects of high-speed ambient flows on contamination, near plume characteristics, and thruster performance with flowing atmospheric species as the predominant background gas, it is important to maintain a very low propellant background gas concentrations relative to the ambient atmosphere. The task of simulating the atmospheric background gas for various altitudes is outlined in Table 1. Using propulsion system with a xenon mass flow of $5 \times 10^{-6}$ kg/s, $n_{B,pr}$ is calculated and compared to the ambient number density ($n_a$) for the TRW (moderate size) [4], Hughes (large) [8], and CHAFF-4 [9] facilities as examples of state-of-the-art test chambers.

Table 1: Parameters of interest for state-of-the-art electric thruster test facilities.

| h (km) | $n_a$ ($m^{-3}$) | $n_{B,pr}$ ($m^{-3}$) | | $n_{B,pr}$ ($m^{-3}$) |
|---|---|---|---|---|
| | | TRW | Hughes | CHAFF-4 |
| 150 | $1 \times 10^{17}$ | $1.7 \times 10^{17}$ | $1.7 \times 10^{16}$ | $4 \times 10^{15}$ |
| 200 | $1 \times 10^{16}$ | $1.7 \times 10^{17}$ | $1.7 \times 10^{16}$ | $4 \times 10^{15}$ |
| 300 | $1 \times 10^{15}$ | $1.7 \times 10^{17}$ | $1.7 \times 10^{16}$ | $4 \times 10^{15}$ |

Note in Table 1 that the $n_{B,pr}$ is equal to $n_a$ at 200 km and is 17 times $n_a$ at 300 km for the Hughes facility. In order to simulate the ambient atmosphere at 200 and 300 km (both operational satellite altitudes) in the Hughes facility, it would be necessary to increase the effective pumping speed by at least a factor of 10 and preferably by $10^2$, a rather substantial task.

The design of CHAFF-4 is an attempt to take a new approach to this problem. Consider the sketches in Figs. 2 and 3 that show schematics of the CHAFF-4 pumping system. The cut-out in Fig. 2 illustrates a cross section of the finned cryopanels, which are held at 20 K. A test thruster operates on the facility centerline producing radial flow that is nearly tangent to the radially arrayed fins. Both high-speed ions and the much slower neutrals impact the graphite surfaces on the $LN_2$ shield, the He coolant supply tubes, and the fin edges. Ions from electric propulsion plumes embed themselves in the graphite ejecting a carbon atom with a probability of about 0.03 [9]. The neutrals partially accommodate to the graphite surface and for the most part stick to the walls of the finned helium-cooled array. Some escape without cryosorbing and return to the interior of the facility as background gas. There is scattering from the finite thickness of the fins, which also returns a flux of propellant molecules to the chamber interior as background gas. Since the mean free path is large, these background gas molecules travel to some other portion of the pumping surface and condense. It is only those molecules that have a direction close to the normal of the two carbon coated surfaces that appear near the thruster as $n_{B,pr}$.

## ATMOSPHERIC SIMULATION REQUIREMENTS

The interactions between spacecraft thruster plumes and the ambient environment have been of interest to many communities for the past several years. The CHAFF-4 provides an opportunity to simulate a variety of on-orbit phenomenon

relating to thruster operation. Applications to material degradation, spacecraft contamination, gas-surface interactions and, in particular, atmospheric plume interactions (plume signatures) are all of interest. Of particular interest in low-Earth orbit (LEO) is the interaction of thruster plume species with atomic oxygen (AO) [10] and solar ultraviolet radiation (SUV). Ion electric thruster plume interactions with the ambient plasma environment have also been of interest recently [11]. The injection of background or simulated atmospheric species in CHAFF-4 can not be done efficiently by simply leaking a gas into the facility since it will be pumped very effectively by the cryogenic system. The injection into the facility can be accomplished by using a variant of a continuum source molecular beam. The continuum source creates a hypersonic beam of molecules from a differentially pumped, doubly skimmed free jet, nozzle, or ion source expansion (Fig. 3). The expansion can be generated by a variety of techniques that have been used for the production of energetic AO and ion beams as discussed in the following sections.

### The Simulation of Atmospheric AO

Atomic oxygen is the predominant species in LEO between 180 and 650 km altitude. AO primarily in the ground ($^3$P) state, results from the photodissociation of molecular oxygen by SUV radiation. With typical number densities of $10^9$ cm$^{-3}$, the flux of AO to surfaces normal to the satellite ram direction is approximately $10^{15}$ cm$^{-2}$ sec$^{-1}$. In the thermosphere (>80 km), AO is present at nearly thermal energies (~ 0.01 eV); however, the relative kinetic energy encountered during collisions with LEO spacecraft (traveling at 8 km/sec) is about 5 eV. Therefore, AO interactions with thruster plumes generally fall into three categories:

(1) AO interactions with low energy (<10 eV), retro-fire plume species,
(2) AO interactions with high energy (>10 eV), retro-fire plume species, or
(3) AO interactions with plume species of any energy in the anti-ram direction.

For low energy, retro-fire plume studies, the energy of the atmospheric species (in this case AO) must be faithfully reproduced for accurate analysis. In this case, the AO energy of 5 eV becomes a significant fraction of the overall relative velocity of the collisional system, which tends to drive the chemical kinetic mechanisms. Chemical and electrothermal thrusters generate low energy plume species. However, the neutral species of a typical ion thruster are also at low energy. AO sources that can produce energies approaching 5 eV with adequate flux levels are generally complex and expensive systems. [12,13]

For high energy, retro-fire or anti-ram plume studies, the energy of the atmospheric species is either unimportant (compared to the incident plume energy) or can be accurately simulated using thermal AO. This greatly simplifies the AO production scheme since energetic AO is not required; however, accurate simulation of anticipated flux levels is still important for studies trying to identify appropriate chemical kinetic mechanisms. Relatively simple microwave discharge production of AO can be used which provides thermal energies at appropriate flux levels [14].

An ideal AO source for plume related studies would be a tuneable energy, tuneable flux source like those initially investigated by Banks et al and his group at NASA Lewis Research Center and Ketsdever et al., [15,16]. Although the investigations into these systems were limited in scope, they showed the potential for tuneable energy atomic beams produced by energy selected, charge exchanged ions. With these systems, collisional energy dependent studies would be possible regardless of the thruster configuration or operating direction. Note that the anticipated mass flows associated with the use of high-speed atmospheric simulations are well within the pumping capabilities of CHAFF-4 (Table 1).

### The Simulation of Ambient Plasma Constituents

The simulation of the ambient plasma environment is accomplished using an ion source that operates on nearly any gas. The ions are produced using a microwave discharge and accelerated to the appropriate energy through electrostatic grids. Electrons can be added downstream of the ion acceleration to charge neutralize the plasma. The ion source is capable of energies ranging from 20 eV to 5 keV. Fluxes on the order of $10^{15}$ cm$^{-2}$ sec$^{-1}$ are possible for nitrogen, oxygen and hydrogen discharge gases. Since the source operates on molecular gases such as $N_2$, $O_2$, and $H_2$, the desired ion (either molecular or atomic) can be mass selected prior to introduction into the main facility.

## CHAFF-4 CHAMBER DESIGN

### Summary of Design Objectives for CHAFF-4

The following is both a summary and overview of the necessary operational parameters that need to be considered before a successful contamination and plume facility can be built. Such a facility should feature the elimination of backscattered molecules in the plume and backflow regions due to sputtering and reflection processes. It should be relatively straightforward to secure a specific thruster and associated optical diagnostics package. Additional access for non-intrusive diagnostic techniques is a design criterion that both maximizes flexibility and addresses unforeseen future needs. The facility must be relatively user friendly and cost effective. The CHAFF-4 design effort used the following specifications and constraints to satisfy the conditions detailed above:

- Minimize diagnostic complications from sputtered/reflected products to a level <<1% of natural plume and backflow number densities by using a series of unique cryogenically cooled panels as well as careful material selection,
- Actuation mechanism that is both precise and accurate on which a thruster and associated optical diagnostics package can be secured (sting),
- 3-axis non-intrusive optical imaging capability which can be adjusted during a test run,
- Incorporate multiple optical ports of various sizes for diagnostics studies; laser-induced fluorescence (LIF), electron-beam fluorescence (EBF), quartz crystal microbalances (QCM), etc.,
- Enhance quick turn-arounds to maximize efficient use of time, and
- Introduce O-atom, plasma and SUV generators to simulate LEO environment.

### CHAFF-4 Dimensions

Since electric propulsion systems produce non-trivial ionization levels with associated energies of 100-1000+ eV, a chamber design must minimize complications due to fast-ion and neutral species. Ions impact surfaces and cause sputtered products to be released [7, 17, 18]. If it were technically feasible to have all propellant products condense on the first surface encountered, a plume facility would only need to be large enough to minimize stray electric field complications as well as allow for undisturbed plume and backflow regions in which to conduct studies. However, despite the use of extensive cryogenic panel systems, there is always a finite possibility that secondary products infiltrate the thruster's environment. Given the physical limit of any cryogenic array subjected to energetic ion bombardment, perhaps the simplest way to help maintain the integrity of the regions of interest is to make the vacuum facility significantly larger than the thruster under study. CHAFF-4 is 6.1 m long with a 3 m diameter as shown in Fig. 4. Compared to existing thrusters, which can have exit diameters ($D_O$) that are roughly a few tens of cm, CHAFF-4's dimensions dominate the relatively small propulsion systems. The closest distance that a thruster would be from the target wall is 3.5 m. Assuming a thruster diameter of 30 cm, the latter would have a maximum solid angle to the target wall that is roughly 0.023 sr. Consequently, there is only about a 1 in 300 chance that a backscattered molecule would find its way to the thruster's vicinity, assuming it managed to escape the cryogenic temperatures of the shield surfaces.

### Chamber Design

In comparison to other thruster evaluation chambers the CHAFF-4 is a moderate size facility. Figs. 3 and 4 show an outline of the CHAFF-4 chamber. On the back door, two 1.0-m diffusion pumps have been placed to remove incondensable gases from the facility (typically He and $H_2$). An adjustable thruster support, which is referred to as the sting, is placed in the center of the castered door. The sting allows longitudinal movements of mounted thrusters and also carries a stepper motor optical system. Optical access to the interior of the chamber is made with several large (25-cm diameter), medium (10-cm) and small (7-cm) viewports. The number and location of these viewports have been selected to provide reasonable diagnostic flexibility. Two viewing stations were placed at one-third and two-thirds chamber-length locations to provide for diagnostic measurements of thruster plumes in the chamber. Each station has three orthogonally placed 10-cm optical ports on the

chamber . In addition to the 10-cm ports, each station has four 7-cm ports that are placed between the orthogonal ports. Quartz and Pyrex glass windows are used in these locations depending on the optical needs. Various vacuum, temperature, high-power, liquid and cryogenic feed-throughs are in place. The associated data acquisition/monitoring systems are implemented using two dedicated computers that are housed in a control room next to CHAFF-4. System monitoring areas will include panel temperatures, LHe/$LN_2$ levels, cryostat operation, chamber pressure and roughing pump status. Power failures and other complications that compromise the safe and efficient operation of CHAFF-4 will initiate automated shutdown procedures.

**Pumping System Design**

Zyrianka 900 Diffusion Pumps

Conventional pumps are necessary to remove incondensable gases such as hydrogen and helium that the cryogenic pumping scheme discussed in the following sections can not pump from the system. Hydrogen and helium are present in the facility from normal atmospheric partial pressures but they can also be introduced as propellants in resistojet or arcjet studies or as atmospheric species. For this reason, the CHAFF-4 facility is conventionally pumped by two Zyrianka 900 diffusion pumps of Russian manufacture shown in Fig. 5. The general dimensions and operating characteristics of the Zyrianka 900 are given in Table 2. Diffusion pumps were chosen to conventionally pump the facility due to the high pumping speeds achievable and low cost per pumped volume. The major disadvantage to using oil diffusion pumps is the potential for chamber contamination from backstreamed pumping fluid.

Turbomolecular pumps, although capable of equivalent pumping speeds of molecular hydrogen and nitrogen, are extremely expensive when compared on a cost per pumping speed level. Oil cooled bearings on turbomolecular pumps can also be a source of oil contamination in the chamber although at relatively low levels as compared with diffusion pumps. Although cryosorption pumps are about half as expensive per pumping speed as turbomolecular pumps, they also have their limitations. Cryosorption pumps can not pump large flow rates of hydrogen and helium for extended periods of time without regenerative procedures.

Table 2: Technical specifications of the Zyrianka 900 diffusion pump.

| | |
|---|---|
| Inlet Diameter (mm) | 932 |
| Height (mm) | 1360 |
| Pumping Speed (l/sec) | Air 25000<br>Helium 42000 |
| Normal Operating Range (Torr) | 5 x 10-4 to 10-8 |
| Pumping Fluid Backstreaming (mg/hr) | 24 |
| Warmup Time (min) | 15 |
| Cooldown Time, Normal (min) | 30 |
| Cooldown Time, Express (min) | 3 |
| Operating Power (Watts) | 14,000 |
| Water Cooling (l/hr) | 600 |
| Weight (kg) | 260 |
| Lifetime to Major Service (hr) | 20,000 |

However, the major feature of the Zyrianka 900 diffusion pump is the pumping fluid backstreaming rate of approximately 24 mg/hr over the inlet diameter. This is nearly an order of magnitude lower backstreaming rate than diffusion pumps of similar size manufactured elsewhere. Although testing is still on going with these pumps, it is conceivable that the pumps can be operated without the use of large cold traps, which are expensive and restrict pumping. The Institute of Thermophysics of the Russian Academy of Sciences has developed the Zyrianka series of pumps by optimizing the interactions of the oil vapor jets with the jet assembly and the pump condensing walls to minimize the backstreaming of the pumping fluid. [19, 20] As can be seen by point 9 in Fig. 5, the oil vapor ring jet from the first stage is pointed toward the pump axis. The effect of this first stage jet configuration is to make the cooled outer casing an effective trap of the backstreaming oil vapor

flow even at large expansion angles. A small water cooled trap is located on top of the ring jet staging to further reduce any oil backstreamed into the facility. If oil contamination into the chamber becomes an issue, contingencies that call for cryo-baffling on the liquid nitrogen panels inside the facility are in place. Note the backstreaming is not directly critical to facility operation because CHAFF-4 has no cryosorption pump, which ~~are~~ is extremely sensitive to oil vapors.

## Cryogenic Pumping

Another integral component of CHAFF-4's unique pumping scheme is a closed-loop gaseous helium refrigeration system. This system, which is referred to as the cryostat, provides a cryogenic source (20 K) for the inner CHAFF pumping surfaces. The cryostat is a refurbished 1950s refrigeration system that was originally designed for the transport of liquid hydrogen by Arthur D. Little, Inc. and Cambridge Corp. [21]. The cryostat is designed to maintain gaseous helium at 20 K while handling a heat load of approximately 200 W. The ability to operate CHAFF-4 using only liquid nitrogen and the cryostat provides a cost-effective means for the evaluation of low-power thrusters without the added cost of liquid helium. Fig. 6 shows the heat load curve for the cryostat at various shield temperatures. This curve represents a conservative estimate of the expected capability (75%). CHAFF-4's inner shield also incorporates a dedicated cryogenic system for liquid helium. This feature gives added flexibility for those occasions where greater heat loading and/or lower pumping temperatures are required.

## Discussion of Finned Array Design

Although maximizing chamber size is the simplest way to help avoid the adverse impact reflected and sputtered species may have on the thruster's plume or backflow characteristics, more sophisticated design issues were considered with special attention given to a cryogenic finned array design and material selection. It is relevant to make some fundamental observations about the manner of pumping utilized in CHAFF-4. Conventional pumping systems making no use of cryogenic schemes have a fundamental pumping speed limit that can be approximated by

(4)

where D and L are the tube diameter and length respectively expressed in cm; and C is the conductance in liters/s. Eq. (4) is representative of molecules undergoing diffuse reflections with the walls of the pumping system in a free-molecular regime. The molecules consequently exit the volume when they encounter the pump inlet. It is important to note that Eq. (4) does not apply for the cryogenic system used in the CHAFF-4 facility. For instance, assume that all molecules eminating from a source within a vacuum facility condense on a cryogenic surface when it is first encountered. The effective pumping speed for such a system would essentially be limited only by the flow rate of the source (forgeting any heat load related surface temperature increase) and is independent of the classic concept of chamber conductance.

CHAFF-4 makes use of strategically oriented cryogenic fins that maximize the collision opportunities between propellant efflux and the cooling array. The geometry outlining the dynamics of this pumping system is shown in Fig. 7. The cryogenic array shown in Figs. 2 and 3 takes advantage of the fact that thermal neutral atoms and molecules undergo predominantly diffuse reflections with CHAFF-4 cryogenic surfaces. In the case of the significantly faster ions, the objective is to allow them to penetrate a surface (graphite) that minimizes sputtering and allows conduction of the deposited heat load.

For the cryogenic system used in CHAFF-4, the pumping speed is a parameter that stems from the unique geometry that emphisizes atom/cryogenic array collisions. The effective pumping speed of CHAFF-4 is fundamentally related to the available cryogenic fin area that is exposed to the plume species. Elevated pumping speeds equate to lower background densities and higher equivalent orbital altitudes. The following expression can be used to estimate the background number density in CHAFF-4

(5)

where is the mass flow, m is molecular weight, is the representative speed of a particular specie impacting into a cryogenic surface, $\alpha$ is the ionization fraction of propellant atoms and $A_p$ is the effective cryogenic pumping area.. Figures 8 and 9 represent anticipated simulation altitudes for various effective pumping area and ionization fractions respectively. The equivalent pumping speed for CHAFF-4 varies between $3 \times 10^7$ and $1 \times 10^8$ liters/s depending on effective propellant speed and exposed pumping area.

Description of cryogenic panel system

Cryogenic facilities have historically been constructed with the maximum pumping area that could be reasonably incorporated [22]. Although available pumping area is also a concern for CHAFF-4, the critical issue for a plume and contamination facility is minimizing sputtered and/or reflected products from the walls. Therefore, CHAFF-4's cryogenic shield arrays were designed to achieve both optimum pumping capability and, more importantly, reduce backscattered molecules to negligible levels.

CHAFF-4 has three aluminum cryogenic systems partitioned into four independent sections. Aluminum was chosen since the cost for using copper was roughly double. First, liquid nitrogen panels ($LN_2$) thermally isolate the relatively hot chamber walls (300 K) from its interior (~20 K). The coverage of $LN_2$ shields will be significant (i.e., >99% of actual chamber wall area - Fig. 3). For a 72 $m^2$ $LN_2$ shields surface area and emissivity of 0.05 (polished aluminum), the associated heat load on the interior of the chamber due to the $LN_2$ shields is approximately 6 W. Second, the cryostat pumping facility will further reduce the interior shield temperature by flowing cooled gaseous helium through a series of tubes welded to the arrayed panels. This will enable a working temperature range between 20-35 K. The cryostat's heat load capacity is approximately 200 W at 20 K. This level of cryogenic cooling is more than adequate for ion engines and Hall-effect thrusters since the propellant of choice for these systems is xenon gas, which is very effectively pumped below ~50 K [23,24]. However, in order to have the flexibility of testing the full range of thrusters (arcjets, resistojets and modest chemical types), a lower operating temperature needs to be possible for the inner-shield arrays. Consequently, there is an option to use liquid helium to reduce the cryogenic panel temperature (<10 K) to combat any complications that stem from elevated heat loading and/or pumping requirements. The liquid nitrogen shield system will take about 1 hour to cool down properly while the remaining cool down time from 77 K to ~20 K using the cryostat will take approximately 10-12 hours.

The shields are shown in various perspectives in Figs. 2 and 3. Using geometric considerations to minimize backscattered molecules was extremely important as shown in Fig. 7. By allowing most efflux atoms through to impact the liquid nitrogen panels, two important issues are addressed:

- First, the solid angle available to atoms sputtered and reflected to the interior of the chamber is greatly reduced. Consequently, a reflected/sputtered atom from the $LN_2$ shield has a high probability of interacting with another cold surface (25 K) before returning to the chamber's interior.

- Second, the liquid nitrogen panels effectively handle roughly 85% of the total heat load produced by thrusters, thereby allowing the cryostat's heat load capability to be used for pumping predominantly thermal atoms rather than wasting available power battling energetic species.

**Sting Design**

It is anticipated that the elapsed time during which diagnostic data can be taken will typically extend for several hours. Therefore, it is important that flexibility be incorporated in CHAFF-4 to maximize data quality and quantity during limited operational test times. A hydraulically actuated sting, shown in Fig. 10, is incorporated in CHAFF-4 on which various thruster types can be secured. The sting allows longitudinal translations (±1 m) of the thruster with a projected accuracy of ±5 mm. Three-dimensional optical diagnostic surveys are accomplished by utilizing a cryogenic temperature resistant stepper motor system attached to the sting. The latter will consist of one rotation and two translation axes (±15 cm). The flexibility of this system will greatly enhance scientific productivity during limited test times since a complete three-dimensional survey can be performed of the plume environment.

The sting arm itself will be shrouded in a liquid nitrogen cooled outer skin to minimize the adverse heat load on the inner cryogenic shield system. The shroud system will also allow for the radiative isolation of the rear and side quadrants of various thrusters further reducing adverse heating of the helium-cooled inner-shield system. The thruster shroud would be an option for research objectives that are not concerned about the backflow region.

Various feedthroughs designed for fiber optics, $LN_2$, power and gas requirements are incorporated at the end flanges of the sting. The respective cabling/tubing is positioned inside the sting with enough yield outside to allow uninterrupted service as

the sting is actuated during a test. Finally, there is a contingency for floating the thruster potential relative ground to investigate the effect of spacecraft charging on operating and plume characteristics.

## CONCLUSIONS

Design objectives for the CHAFF-4 contamination and plume diagnostic facility have been outlined. The need to perform plume studies and obtain contamination footprints drove CHAFF-4 designers to pursue a different approach with respect to cryogenic pumping than is traditionally used. Development of an extensive multi-finned cryogenic shield system (590 $m^2$ maintained between 20-35 K) results in significantly lower background densities than is typically found in facilities of this kind (with lower limits between 5 x $10^{14}$ and 4 x $10^{15}$ $m^{-3}$). Equivalent test altitudes ranging between 150-350 km are possible depending on thruster operational specifications. The associated pumping speed is driven by the cryo-cooled surface area that interacts with propellant species and varies, depending on thruster type, between 3 x $10^7$ and 1 x $10^8$ liters/sec. The facility is cooled by a cryostat system that enables the testing of a range of thrusters, up to a power level of approximately 3500 W, without resorting to supplementary liquid helium. In addition, it is possible to introduce liquid helium for those occasions when it is warranted. An analysis to protect the facility against ion-driven sputtering erosion resulted in the use of strategically positioned graphite layers.

It will be necessary in the near future to perform detailed shakedown and performance tests to establish the actual operation envelope of CHAFF-4 and to validate the design principles. Finally, the greater goal for the Collaborative High-Altitude Flow Facility is to develop a detailed understanding of the complications and/or advantages inherently found in this type of facility, and to bring about more effective strategies for investigating space propulsion systems.

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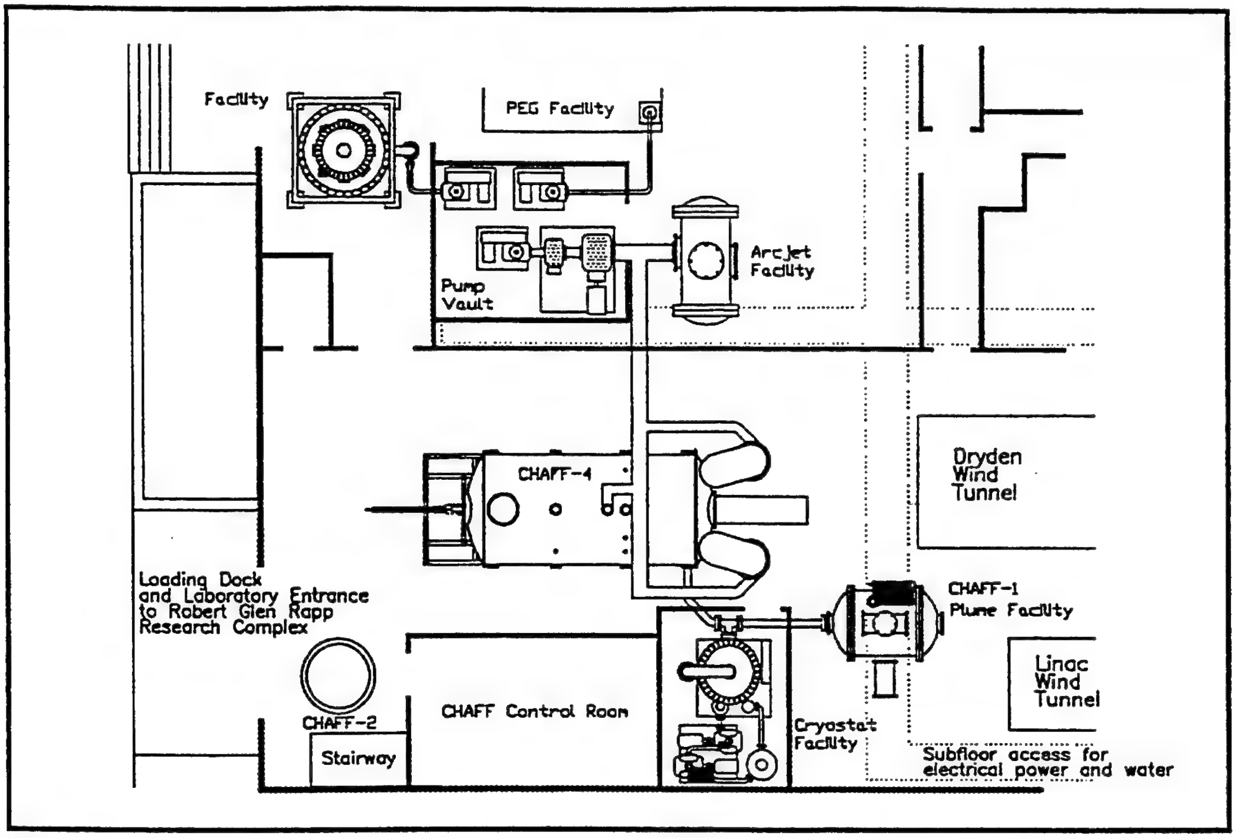


Figure 1: Layout of the David P. Weaver Collaborative High Altitude Flow Facility at USC.

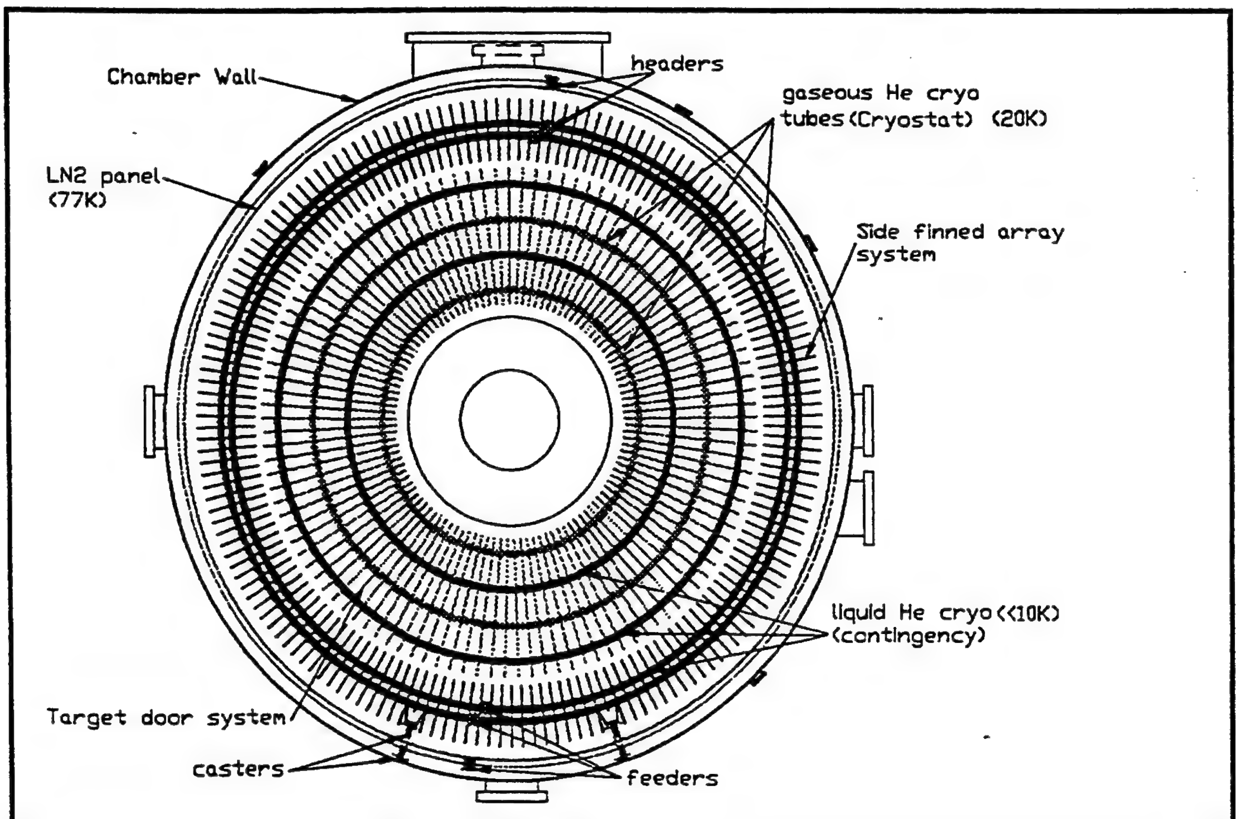


Figure 2: Front view of CHAFF-4 cryogenic array system.

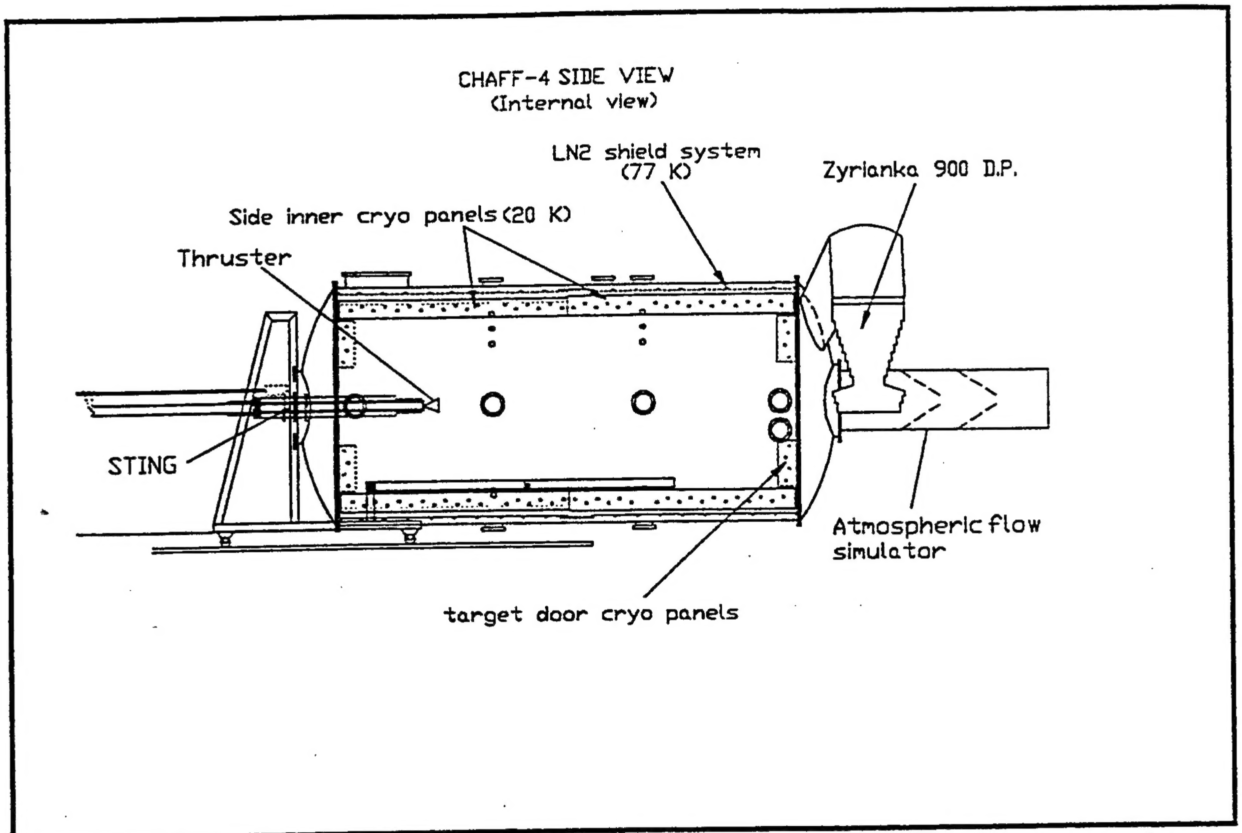


Figure 3: Side view of CHAFF-4 cryogenic system, STING apparatus and atmospheric flow simulator.

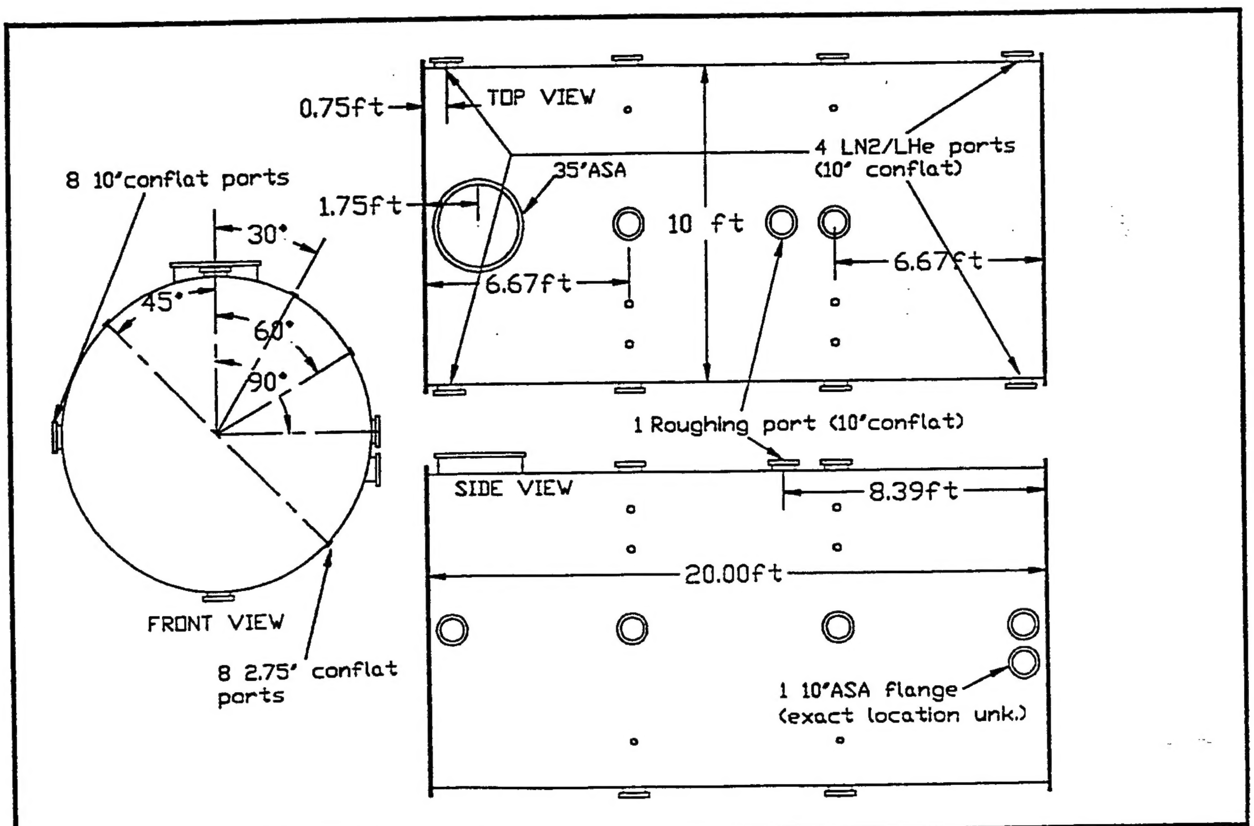


Figure 4: Blow up view of inner cryogenic shield geometry under ion bombardment.

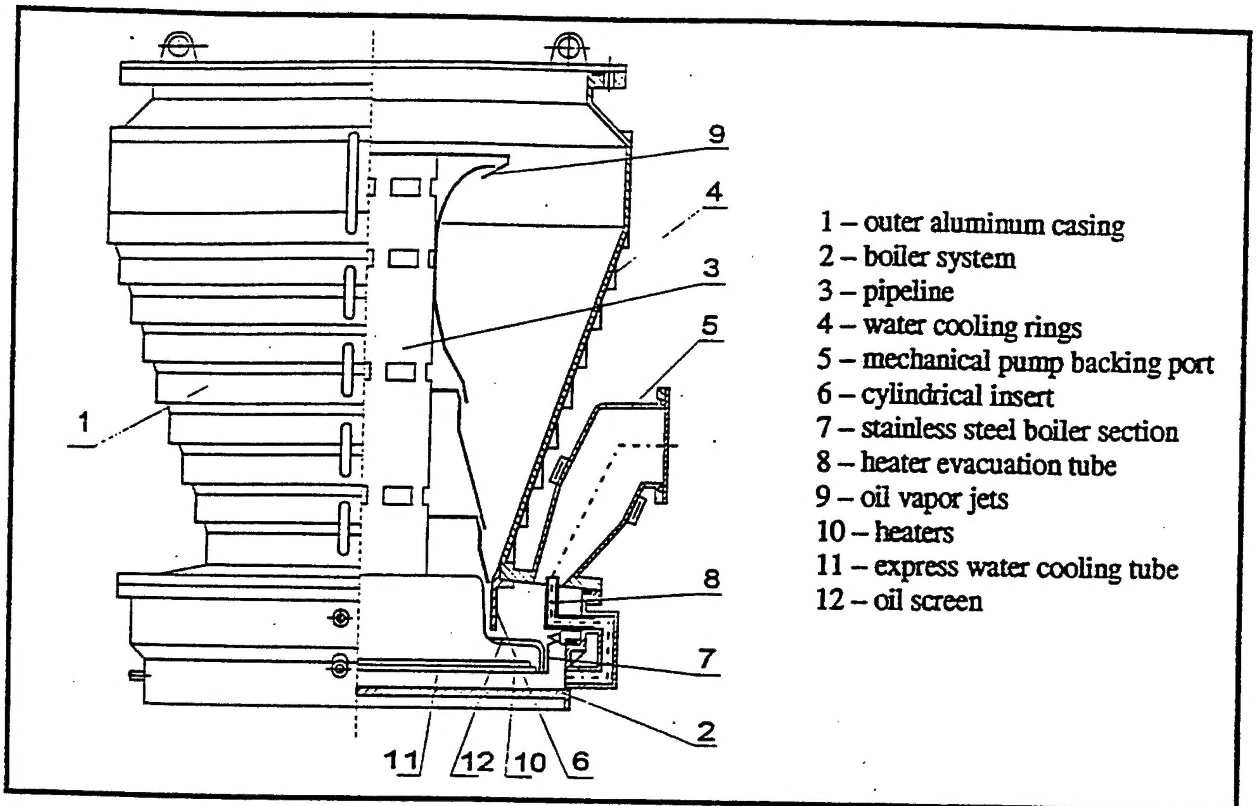


Figure 5: Zyrianka 900 diffusion pump schematic.

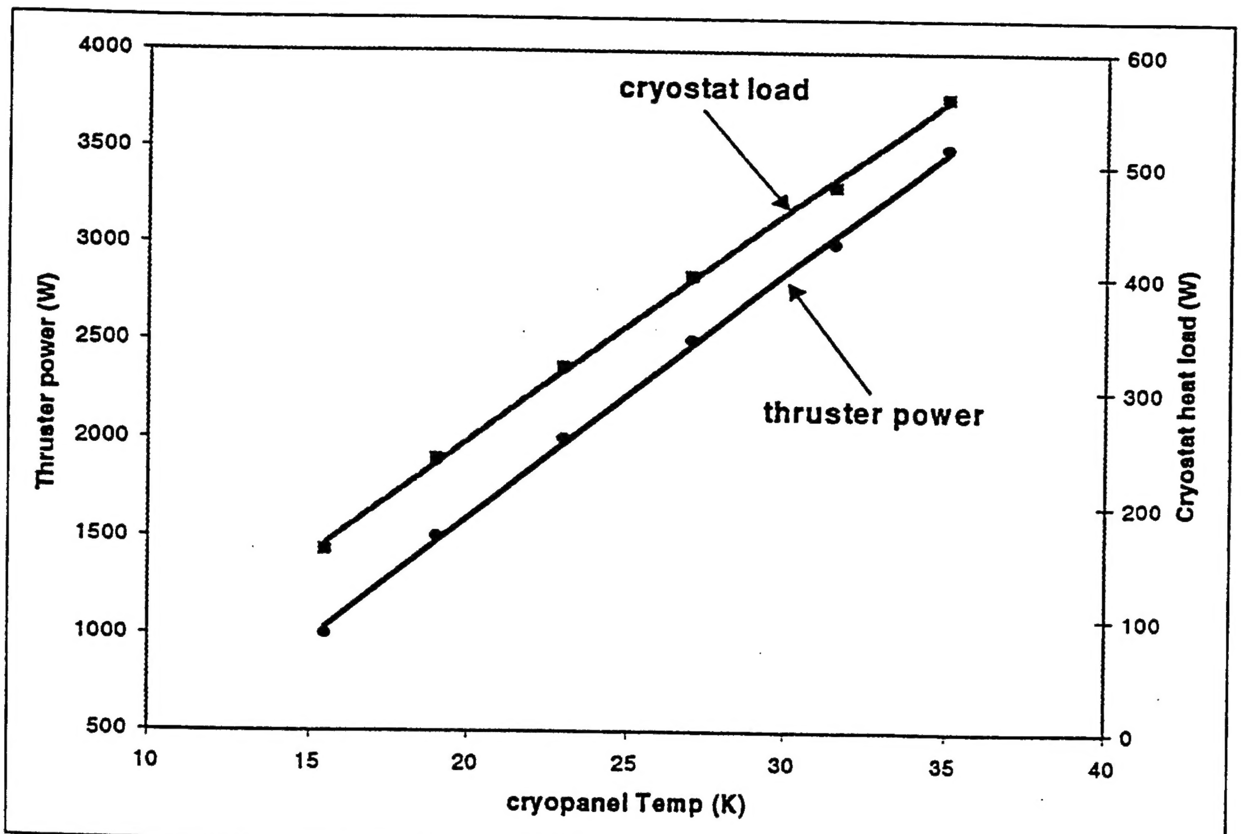


Figure 6: Heat load characteristics of CHAFF-4's cryostat vs inner shield array temperature.

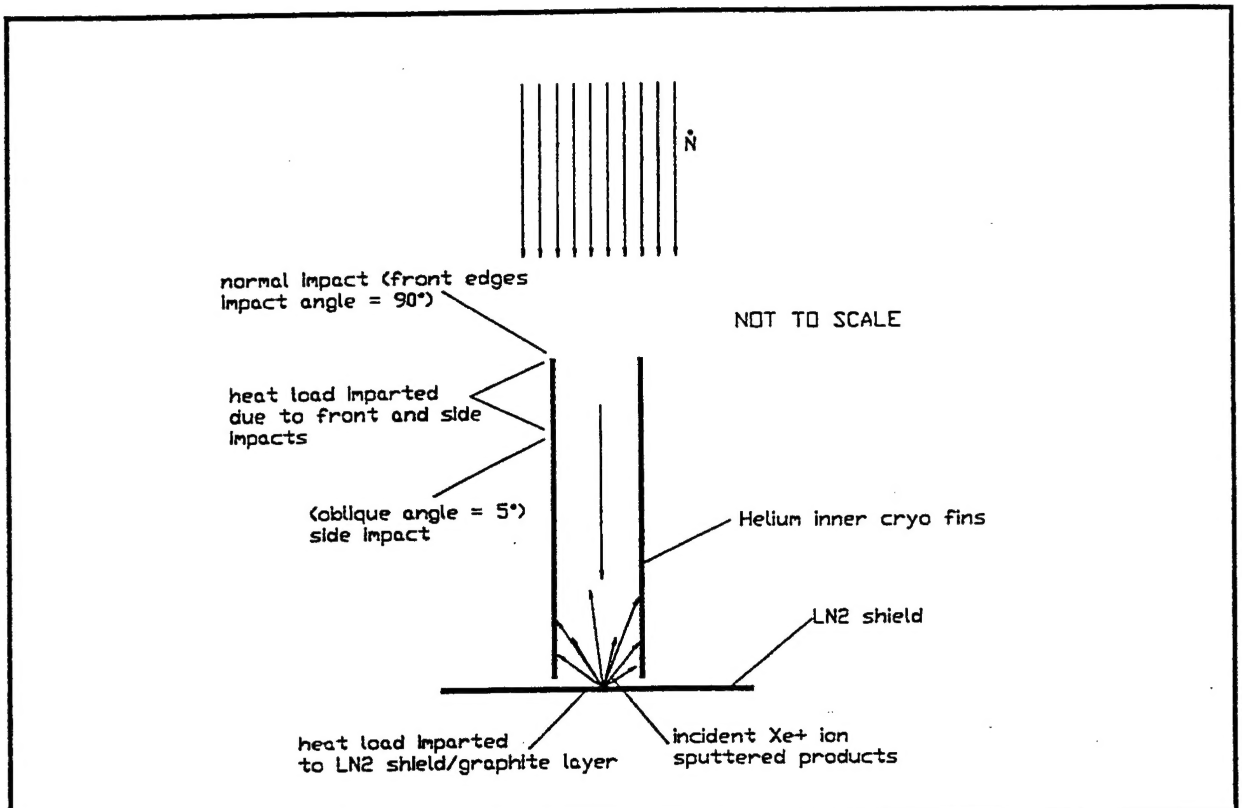


Figure 7: Blow up view of inner cryogenic shield geometry under ion bombardment.

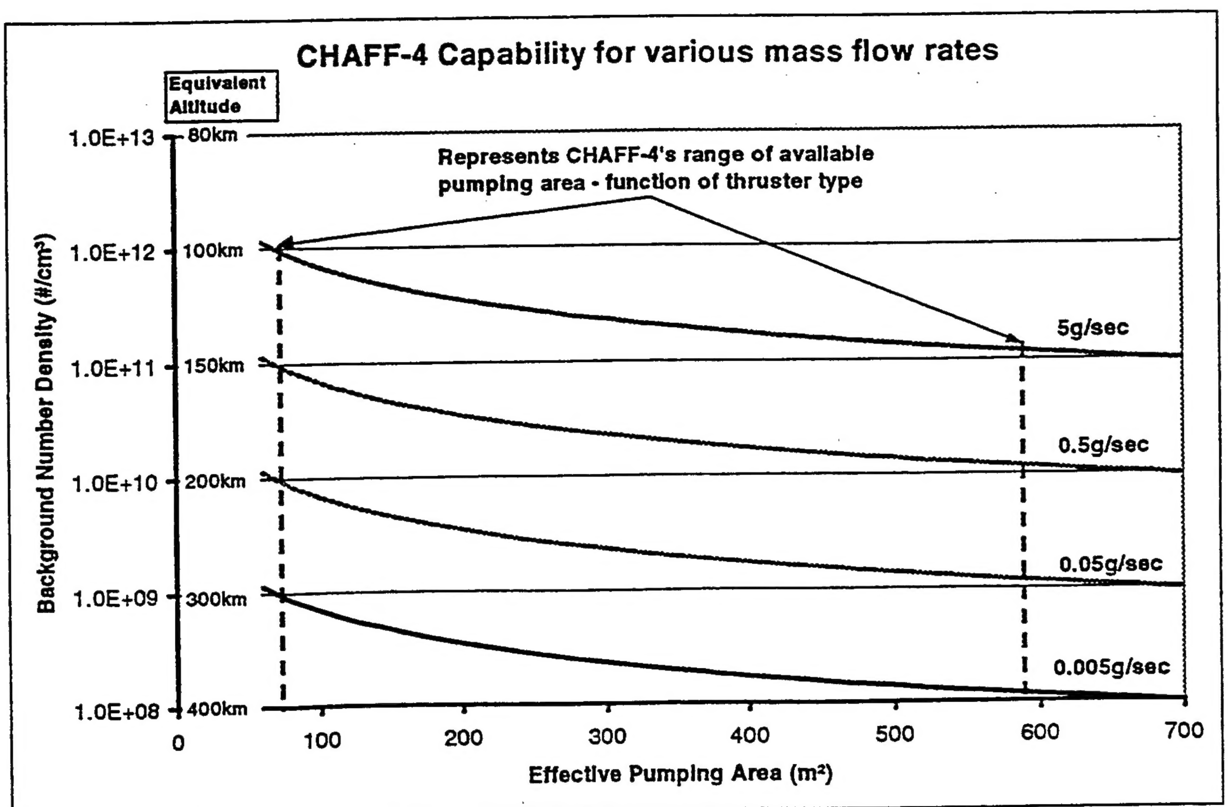


Figure 8: Background density and equivalent altitude capability versus effective pumping area.

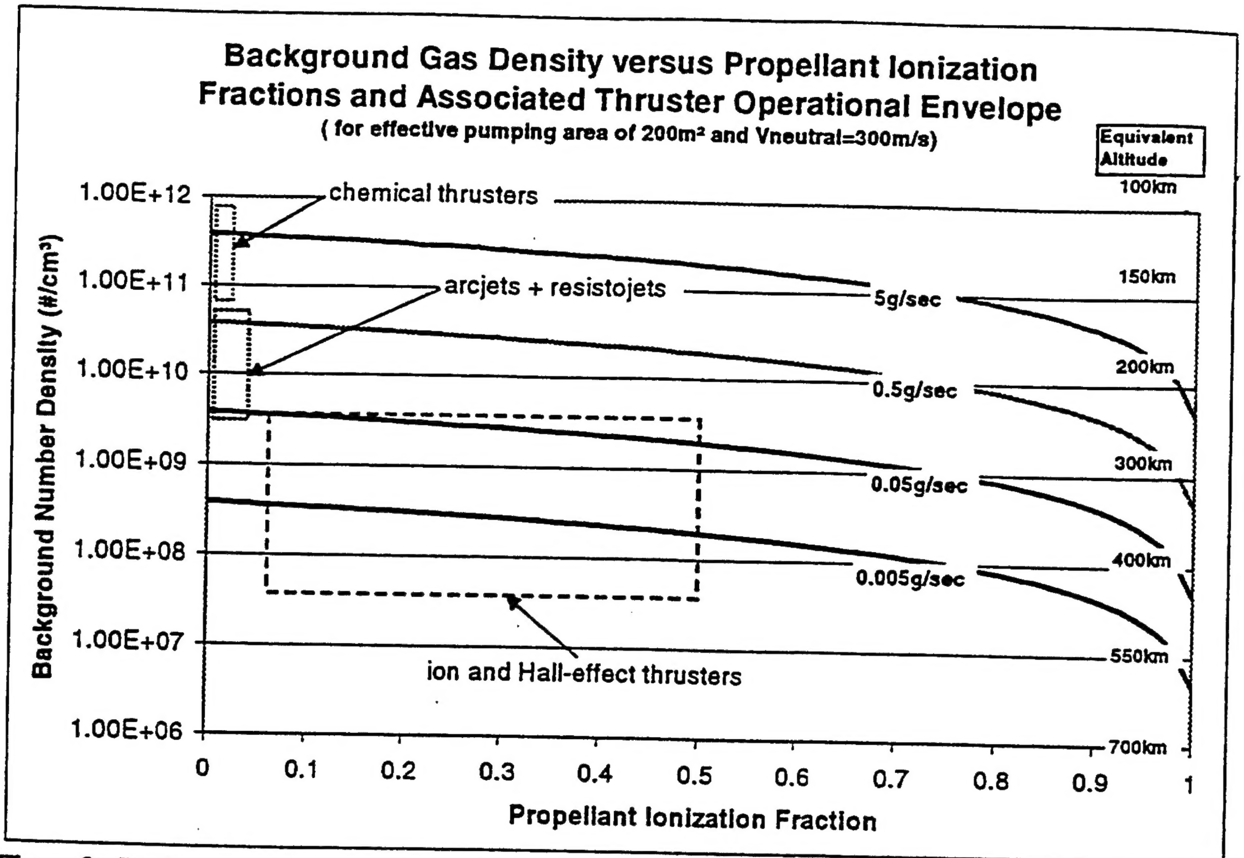


Figure 9: Background density and equivalent altitude capability versus propellant ionization fraction.

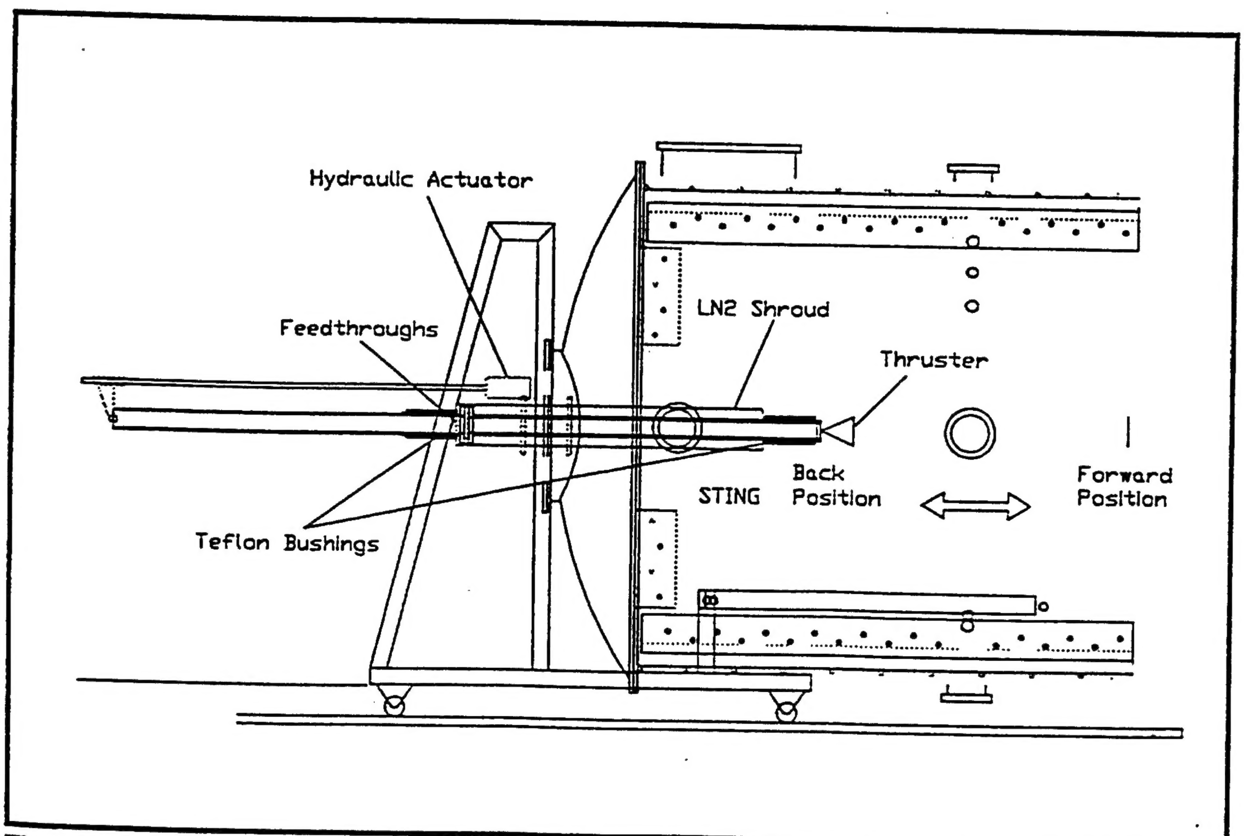


Figure 10: CHAFF-4's STING apparatus.